A Computational Framework for a Multi-Agent Simulation of Freight Transport Activities

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ABSTRACT

It is widely recognized that micro-simulation and agent-based approaches can successfully be applied in transport policy analysis. However, logistic decisions and the complex relationships among freight actors make this a challenging task and a reason why the development of freight models is still behind the development of passenger models. In this paper, we present a multi-agent freight transport model in which logistics decisions are separated into different roles: the shippers, which decide about shipment frequency, the transport service providers, which create transport chains, and carriers, which plan tours and schedule vehicles. All agent types can consolidate freight on their respective level and realize economies of scale. The lowest tier of the model, which contains individual freight vehicles, is integrated into the MATSim traffic simulation to create an integrated model for freight and passenger traffic. Changes in passenger demand, disturbances in the traffic system or policy measures can be picked up by freight drivers and propagated upwards to influence decisions on the levels of vehicle scheduling and transport chain building, and further on the level of shippers. As proof of concept, we set up a scenario with fictitious freight actors serving a set of customers. We demonstrate that freight traffic can be simulated under different traffic conditions and policy measures.

INTRODUCTION

It is widely recognized that micro-simulation and agent-based approaches can successfully be applied in transport policy analysis. However, the development of freight micro-models is still way behind the development of passenger transport models. Recently, however, several promising freight micro-models have been developed. The achievements can be clustered into two groups of models: The first model category transmutes freight flows into shipments and shipments into truck tours (see, for instance, the models described by Ramstedt (2008), Wisetjindawat et al. (2009), Liedtke (2008) and De Jong et al. (2007)). Furthermore, Roorda et al. (2010) proposed a conceptual framework for agent-based modelling of logistics services. The models belonging to the second category - the tour-based models - focus on the execution of complex tours in space. Hunt and Stefan (2007), for instance, set up a tour-based micro-simulation of urban commercial transport movements. Joubert and Axhausen (2010) developed an activity-based model for commercial transport in Gauteng, South Africa.

Whilst the models based on commodity flows and shipments mostly address inter-regional, national and international transport planning, the tour-based models are generally used for modelling commercial transport in agglomerations and big cities.

For the moment, however, most freight models focus on certain aspects of the model object. They do not map all relevant logistics decision makers and decisions, respectively. Important logistics decisions such as shipment size/frequency, warehouse location and vehicle routing are disregarded or considered only implicitly. There is still a lack of policy sensitive models in order to assess incentive-oriented policy measures and regulations as well as new logistics schemes. To build such a model, a detailed representation of logistics decisions and activities such as 'consolidation', 'distribution', 'pick-up' and 'delivery' is necessitated. Since these activities require the use of physical transport networks where not only freight operators but also passengers compete for capacity, an integrated multi-agent simulation of both commercial and passenger transport is indispensable.

This paper attempts to fill at least part of the gap towards a policy sensitive model by presenting a computational framework for an integrated multi-agent logistics and commercial transport model. It focuses on the detailed representation of the agents in the freight transport system. We identify the shipper and the transport service provider to be key decision makers, and model them as software agents participating in the multi-agent passenger simulation MATSim (see Balmer et al., 2009). The present paper extends the work of Schroeder et al. (2011) in which the role of the transport service provider and the integration of freight agents into MATSim have been elaborated

The paper is organised as follows: After these introductory remarks, section 2 sets up the background for our work compiling findings from literature on transport research. Then, we briefly present MATSim, the multi agent passenger simulation. Section 3 deals with our representation of the shipper and the transport service provider. We model the shipper and transport service provider as four distinct agents: The *Shipper Agent*, the *Transport Service Provider Agent*, the *Carrier Agent* and the *Driver Agent*. In section 4 a scenario is constructed in which a fictitious freight operator serves a set of customers. We demonstrate that freight traffic can be simulated under different traffic conditions and policy measures. A conclusion and an outlook finalise the paper.

BACKGROUND

Literature overview on micro freight models

In literature, we basically identify two types of micro freight models: commodity flow based and tour based models. The commodity flow based models are typically used to model commercial transport at an inter-regional level, whereas tour based models are applied to model commercial transport in agglomeration and big cities.

De Jong and Ben-Akiva (2007) develop a logistics module for a commodity flow based model in Norway and Sweden. In a sequence of operations, commodity flows between regions are transformed into vehicle-flows. During this process the model focuses on two major logistics decisions: Frequency and shipment size decision as well as transport chain choice. The first are decisions related to shippers and receivers. The latter is a typical decision of a transport service provider that can be further subdivided into the following sub-decisions: (i) Choice of the number of legs in a transport chain, (ii) choice of the use of distribution/consolidation centres and (iii) mode choice for each leg including (iv) choice of vehicle/vessel type and (v) loading unit. Wisetjindawat et al. (2007) develop a micro simulation for modelling urban freight movements. They extend the traditional four-step approach by including logistics decisions such as shipment size and frequency choice, carrier choice, vehicle type choice and routing.

Several recent publications represent individual actors as multiple agents. Some of the advantages are the ability of focusing on certain behaviour explicitly. In agent based models market coordination, learning capabilities, restricted agents' perception of the environment and different decisions relating to different time horizons can be mapped. Liedtke (2009), for example, develops such a model for Germany. He explicitly models the decision of two main agent-types: The shipper and the carrier. Shippers can decide about shipment size and carrier choice. Carriers construct truck tours with a vehicle routing heuristic. Both iteratively interact with each other in a market environment and make experiences from past iterations. Roorda et al. (2010) set up a conceptual framework for agent-based modelling of logistics services. They identify a number of agents, their respective behaviour and important facilities in the freight system. The agents coordinate by means of contracts. The contracts are a result of market interactions. Shippers make shipment size and frequency decisions. Shipper-Carrier relationships are set up by logistics contracts. Given those logistics contracts the carrier conducts a number of logistics decisions to fulfil them. First, the carrier decides about the transportation mode, which includes the possibility of using trucks only as well as intermodal combinations of truck, rail and marine. Secondly, for each of those transport modes – in the following we name this transport chain – further consolidation decisions are conducted. That is, for each leg in the transport chain, vehicle type choice, vehicle scheduling and route choice is made. Ramstedt (2008) design a multi-agent based simulation of transport chains. They identify the transport chain coordinator (TCC), the transport buyer (TB) as well as the transport planner (TP) to be key decision makers on the supply side of transport market. The TCC is the interface between product demand, production and transportation choice and matching product suppliers with transport service providers. The TB manages the transport chain and its corresponding legs. The TP is the carrier actually owning a vehicle fleet and conducting the physical movement. Thus, transport chain choice and carrier choice are explicitly modelled.

Wrapping this up, a number of researchers currently include shippers and transport service providers as autonomous actors in their commodity-flow based freight-model. The models map consolidation processes on different levels. In transport logistics, there is consolidation on the level of warehouses, on the level of transport chains (distribution or generally in transhipment centres), and on the level of vehicle tours. Or to put in other words, economies of scale can be realised both in logistics facilities and within vehicles. These two levels cannot be seen as independent. The consolidation processes are basically modelled by the following decisions: Shipment size and frequency choice, transport chain choice, vehicle type choice, vehicle routing and scheduling decisions.

Urban commercial transport differs from long-distance (commercial) freight transport in a number of ways (see Hunt and Stefan (2007)). Firstly, certain transport modes are mostly irrelevant for urban goods movements, e.g. rail and marine. Secondly, urban commercial transport is not solely related to goods movement, but also includes movements of persons and services. And finally, transport in cities only relates to certain sub-systems of the interregional transport and logistics systems.
Micro-modelling of urban commercial transport is mostly done by the means of tour-based models. Hunt and Stefan (2007) develop a tour-based micro-simulation of individual vehicle movements. They estimate the number of tours in their study area Calgary and construct these tours with a tour expansion process. In this process, they successively assign tour attributes to each tour, i.e. vehicle type, vehicle purpose and starting time. Given those attributes they iteratively let the tour grow by assigning next stop purpose, next stop location and next stop duration. A return trip to where the tour has started closes the tour-expansion. Joubert et al. (2010) apply a tour-based approach to simulate a large-scale scenario of both private and commercial vehicles in Gauteng, South Africa. They define a tour as a sequence of commercial activities and derive those activities from GPS-logs. Based on that, they deduce conditional probabilities to construct commercial activity chains in time and space. Together with passenger activity-chains these commercial activity-chains are then simulated with the multi-agent simulation toolkit MATSim.

However, the majority of urban commercial transport research still uses a level of abstraction once it comes to the mapping of logistics decision makers and their decisions. Particularly, decisions on shipment-size/frequency, warehouse location, vehicle type, vehicle routing and scheduling are disregarded or considered only implicitly. In contrast, most of the commodity-flow based models represent vehicle tours only in a very simplified manner. Similarly, tour based models neglect commodity flows. We identify the Transport Service Provider to be the interface between the commodity-flow based and tour based approaches. However, decisions about commodity flow and tours require different views on the transport system. The commodity flow view contains a hyper-network where links represent means of sending goods from one location to another. The tour view relates to vehicle movements in physical networks. MATSim has become a mature simulation framework simulating passengers as agents in physical networks. Passenger vehicles and freight vehicles use the same road network concurrently. Consequently, MATSim is an ideal framework to cover the representation of freight agents in physical networks.

MATSim: Passenger Simulation

The travel demand model implemented in MATSim consists of a set of agents representing individual users of the traffic system. Every agent is equipped with a *plan*, which describes locations, times and types of all the *activities* the agent will conduct, with *legs* connecting each physical activity location to the next. Legs can be travelled using different transport modes and, depending on the transport mode, along different routes through the transport system. A choice for all of these options is encoded in the plan.

All agents simultaneously execute their plans in a concurrent simulation of the transport system. The simulation picks up congestion effects, missed public transit connections, delayed arrivals at activity locations, and other effects of multiple agents concurrently using the traffic system. The result of the simulation is fed back to the agent as experience, and it is used to score the plan using a *utility function*, which can be personalized for each individual, for example by depending on their age or income.

At the beginning of the next *iteration*, some agents obtain a new plan by creating a modified copy of one of their existing plans. This is done by several *modules*, which correspond to the choice dimensions available to the agent. One module chooses a new route, while another switches the transport mode, and yet another chooses new times for activities. This step in the process is called *re-planning*. Agents select one of their plans according to a *random utility model*.

The planning and re-planning model employed here is obviously tailored to passengers. Up to now, real-world scenarios set up with MATSim have modelled the freight traffic share of the demand by using a set of plans with two activities labelled *freight-origin* and *freight-destination*, connected with a single leg, and with no variability in any choice dimension except route choice. Freight traffic has essentially served as a background load of the traffic system, without much adaptive behaviour. One of the aims of this paper is to improve on this situation by modelling freight vehicles as non-autonomous agents employed by and serving the interests of transport service providers, which we add to the model. The missing choice dimensions of freight vehicle drivers are then realised as logistics decisions made by transport service providers.

METHODOLOGY – AGENT'S VIEW

The shipper and the transport service provider are the key decision makers in a freight transport system. We introduce software agents for shippers and transport service providers and determine the types of decisions available to them, which are most relevant for our transport model. These decisions lead to a *plan,* which consists of planned actions in time and space. The decision-making is based on *knowledge* about the transport system, *capabilities*, which are static individual attributes of the agent, and *contracts* defining business relationships to other agents. The agents, their decisions, knowledge, contracts and plans are described in the next sections.

The shipper is responsible for finished products to be sent either as intermediate products to manufacturing plants, or as final products to wholesalers and consumers. In our model, it is represented by a Shipper Agent. The transport service provider is responsible for transporting freight from the senders to the recipients. To reduce complexity and to take into account its different roles, we decided to model the transport service provider as two distinct agents: the *Transport Service Provider (TSP-)Agent* and the *Carrier Agent*.

Shipper Agent

The contracts of the Shipper Agent represent business commitments to serve firms and consumers with the underlying product. The contract determines type, value and quantity as well as the respective origin and destination of the product. Usually, this corresponds to the demand in a certain time span, for instance a week, month or year. It is thus considered here a commodity flow.

The capabilities of the Shipper Agent include the warehouses which it has at its disposal in order to consolidate commodities in time. In our current implementation, the shipper is allowed to use a warehouse at the origin and the destination location of a commodity flow. Warehouses are usually subject to long-term decisions of the shipper. For the moment, they are thus assumed to be static attributes.

Given its capabilities and knowledge about the transport supply, the Shipper Agent plans the fulfilment of its contracts. Therefore, for each commodity flow, it decides about how many shipments are required to send the whole quantity of the commodity flow to the respective destination. This is usually referred to as shipment size and frequency choice, and it implies scheduling of these shipments in time as well, i.e. earliest/latest pickup and delivery times. Additionally, but not independent of the latter decisions, the Shipper Agent chooses a transport service provider to carry out the transportation.

For example, a very simple plan is to ship the whole quantity of the commodity flow at once, which results in one shipment, whose size is equal to the size of the corresponding commodity flow. Such a plan might result in comparably low transportation costs. On the other hand and depending in particular on the value of the product, it might induce high inventory costs (if we assume a constant demand by the receiver). Hence, shippers are likely to plan their shipments such that total cost are minimised. In literature, these total costs are referred to as total logistics costs; and among a variety of other cost variables, transportation and inventory costs are influential cost components. Describing these components in the concise words of Sheffi (1986), "inventory costs (can be thought of) the costs associated with moving freight through time, while transportation costs are the charges for moving the freight through space". Whereas marginal inventory costs are especially affected by attributes of the Shipper Agent and the value of the underlying commodity, marginal transportation costs are very much influenced by the transport supply. Here, transport supply is represented by the set of transport service providers.

Transport Service Provider Agent (TSP Agent)

The *contracts* of the TSP Agent are manifestations of business obligations to shippers. The contract determines type and quantity of goods to be shipped, their respective origin and destination, as well as the price the shipper has to pay for the service. A "transport service" or "shipment" constitutes an elemental movement of a good from a sender to its recipient.

Each TSP Agent is attributed with *capabilities*. Currently, these are transhipment centres this TSP can use.

Based on his knowledge, the TSP Agent can plan the fulfilment of his contracts. For each shipment, the TSP agent creates a transport chain and chooses a carrier for operating each leg.

A transport chain is the sequence of logistics activities and carriers a shipment takes on the way from the sender to the recipient. In our basic model, the TSP Agent can schedule two types of logistics activities: Pick-Up and Delivery activities. A leg is what happens between a pick-up and a delivery activity. The simplest transport chain is the direct chain from the sender to the receiver. More sophisticated transport chains emerge when a TSP operates with a hub-and-spoke network. A transhipment activity is then represented as a Delivery followed by a Pick-Up at the same location.

Each leg of a transport chain is an elementary movement and shipment. For each of these shipments, the transport services of different carriers can be contracted. For example, for the initial and the last leg, a local road carrier could be chosen, whereas a transnational railway company could operate the main leg. Such a transport chain is called an intermodal transport chain.

To summarise, the TSP Agent is modelled as the organizer of the transport chain. Its plan is still shipment related rather than vehicle related. We view scheduling and routing of vehicles as tasks of a different role, the role of the Carrier Agent.

Carrier Agent

Carrier Agents have contracts, which, just like the contracts of TSP Agents, determine type and quantity of goods to be carried. A carrier contract contains the respective origin and destination as well as pick-up and delivery time windows. The contracts describe business relations. For our purposes, the customer party in these contracts will be a TSP Agent, but this part of the model can be generalized so that the carrier agent can be responsible for services and the movement of passenger. In that case, the customer would be a household or an entirely different type of agent.

Carriers obtain contracts from TSP Agents by making offers for their services. A TSP can obtain an offer from a carrier by stating origin, destination and shipment size, and the carrier will respond with a price. The TSP then picks an offer and assigns the contract to its preferred carrier. For simplicity, we decided against implementing a more sophisticated market model where a carrier can turn down a contract. Carriers accept every contract for which they have made an.

Since the Carrier agent is designed to model a transport operator, its capabilities include the locations of its depots and information about its vehicle stock.

The most relevant decisions of a Carrier Agent are:

- Mode choice (including the choice of different types of vehicles) and
- Vehicle routing and scheduling

The plan of a Carrier Agent thus contains a set of vehicles, each equipped with the schedule of a tour. The schedule contains planned pick-up, delivery or arrival times at customer locations and a route, which is the actual path through the physical network. In our basic model, all vehicle schedules begin and end at a depot.

In the physical layer of MATSim, the basic unit of simulation is a vehicle with its driver. Accordingly, at the interface between the freight operators' mental layer and the MATSim mobility simulation, the set of routed vehicles of each Carrier is injected into the traffic demand as individual *Freight Driver* agents. These agents use their tour schedules in the same way as passenger agents use their activity plan.

We modelled Transport Service Providers and Carriers as different roles (and different agent types) in order to create a framework where the coordination between these roles can be as complex as a full-blown transport service market or as simple as arbitrary assignment. It is still possible to represent the case where the two roles are held by a single entity, simply by having one or more carrier agents deal exclusively with one TSP agent, and giving them complete knowledge about each other. Such a composite agent could be used to model a multi-modal transport service provider, which executes a complete transport chain with its own resources.

SIMULATION

A simulation run can be broken down into the following steps:

1.) Initialise the world.
2.) Construct the initial plans of various agents.
3.) Execute the mobility simulation.
4.) Calculate scores.

5.) Let the agents improve their plans.

Steps 3 to 5 are repeated until a relaxed state is reached.

In **Step 1,** we initialise our model environment. This amounts to creating the physical networks and the population of shippers with its warehouses; the population of transport service providers with the locations of their transhipment centres; and of the carriers with the locations of their depots and their vehicle fleets.

In **Step 2,** an initial plan is created for each agent. Shipper Agents determine shipment size and frequency based on offers requested from TSP Agents, resulting in a set of contracted shipments. TSP Agents, in turn, create transport chains to fulfil their set of shipment contracts. Each leg of every transport chain is contracted to a carrier. The carriers then create a schedule for each of their vehicles, including a complete route through the transport network, with pick-up and delivery activities corresponding to their transport contracts. All agents can base their decision strategies on initial information about the transport system, taking into account the restrictions imposed by their limited capabilities. Routes, for example, are chosen on the basis of travel times on an empty road network.

These initial freight traffic plans are then injected into the mobility simulation of MATSim, where they are represented as vehicle agents moving through the traffic system along with passenger vehicles. In **Step 3**, all these agents concurrently execute their plans and experience the constraints of the physical network. While executing their plans, the agents report their shipment-related activities back to the carrier.

In **Step 4,** agents evaluate the success of their plan. The MATSim passenger model uses a utility function tailored to evaluate the outcome of a travel plan for a person on a typical workday. In contrast, the freight traffic agents introduced here have to use a custom utility function that captures their economic success. Carriers calculate their cost as a sum of vehicle-dependent distance and time costs incurred by their scheduled vehicles and some individual fixed costs. The transport service providers calculate their cost as the sum of the fees they pay to carriers, plus opportunity costs incurred by missed time windows. Shippers calculate total logistics cost, by determining, for instance, transportation and inventory cost. Whereas transportation cost are calculated by summing up fees from transport service providers, inventory cost are determined by evaluating shipper's average inventory stock.

In **Step 5**, agents create new plans to try to improve their performance in the next iteration. For instance, a time dependent vehicle routing heuristic can be plugged-in to re-plan vehicle schedules. Carriers could choose to only re-plan the routes of their drivers, or they could switch shipments between vehicles, or even add or remove an entire vehicle. This is also the point where carriers update their tariff table. The Transport Service Providers in turn can re-plan the layout of the transport chains and the assignment of commissions to Carriers, after obtaining new offers which the carriers make using their updated pricing scheme. Given the pricing scheme of the Transport Service Provider, Shippers can try to reduce total logistics cost by replacing inventory through transportation. They can increase shipment frequency, for example. Or, they can switch to another transport service provider offering better services. It is important to note here that agent's re-planning can be as simple as single local changes or as complex as sophisticated optimization algorithms. However, changing the strategy of one agent might imply a modification of contracts of another agent. Therefore, one important issue at this point is how agents incorporate changes in their set of contracts into their plans. If they use a scheme where the plan is computed in one step as a function of the set of contracts constrained by their capabilities, this is not an issue. But if a genetic algorithm approach is taken, where applying small local modifications to a previous plan generates the new plan, a way of adapting the new plan to the possibly changed set of contracts must be provided.

During repeated executions of their plans, passengers as well as Carriers, Transport Service Providers and Shippers collect experience from the transport system. The carriers pick up congestion and other disturbances in the traffic system when they incur a higher cost through longer vehicle usage, or by penalizing missed pick-up and delivery times. The cost incurred by carriers is incorporated into their pricing scheme and in turn picked up by the transport service providers, who can react by switching their contracts to different carriers or modifying their transport chain.

PROOF OF CONCEPT

We implemented the multi-agent model presented here, integrated it with MATSim and set up a scenario for a case study. It is important to mention that at this point that we are focussing on the functional features of our model environment rather than on sophisticated behavioural models. We demonstrate interactions among shippers and freight operators by simulating them under different transport conditions, e.g. after the implementation of policy measures such as a city toll.

Scenario

Our scenario is based on two time periods and a simple 8x8 checkerboard with a spike. The checkerboard represents a simplified urban area. It is an undirected graph where all nodes and links have equal characteristics. Each link has a length of 1 kilometre, a capacity of 1000 vehicle per hour and a design speed of 50 km/h. The spike represents the connection from our city to a distant industrial location. It is 80 kilometres long and has a design speed of 100 km/h.

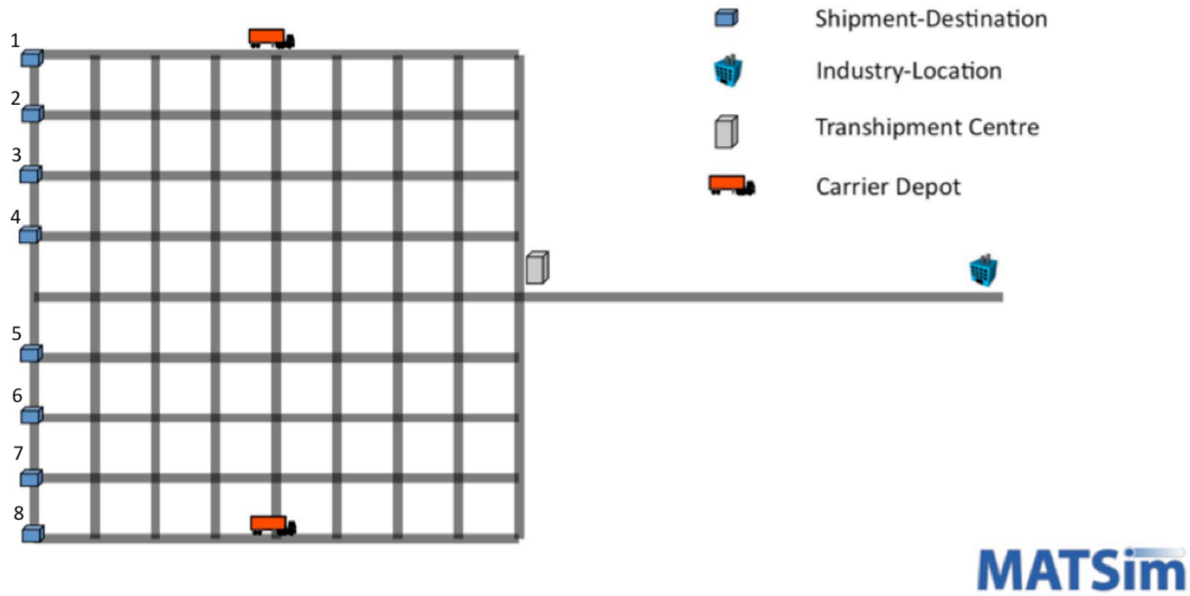

Figure 1: Scenario

The freight agents are modelled as follows:

Shipper Agent

We model four Shipper Agents, each producing commodities at the industry location. Its contracts are listed in Table 1. Each contract defines a commodity flow originating on the right hand side of the spike, and ending at the corresponding consumer on the left hand side of the urban area (see Figure 1). For instance, Shipper Agent 1 has committed to consumer 5 to send 10 units with a value v of 3500€ per unit. Each shipper is provided with a warehouse at the consumer's location. For simplicity, we assume this warehouse to be the only possibility to consolidate commodities in time, even though production processes might require commodities to be stored at the respective production location as well.

Table 1: Shipper Agents and its commodity flows

Shipper	From	To	Size	Value
Shipper 1 (High Value)	Industry	1	10	3,500
		3	10	3,500
		5	10	3,500
		7	10	3,500
Shipper 2 (Low Value)	Industry	1	10	500
		3	10	500
		5	10	500
		7	10	500
Shipper 3 (Mixed Value)	Industry	5	10	1,200
		6	10	1,000
		7	10	2,030
		8	10	1,500
Shipper 4 (Mixed Value)	Industry	1	10	1,170
		2	10	2,510
		3	10	1,600

	4	10	2220

With regard to the *behaviour*, Shipper Agents can choose to either send the quantity Q of 10 units at once, or to send it as two shipments, i.e. five units in the first and five units in the second period. This frequency decision results in shipments with a size of q and is made upon a trade-off between inventory and transportation costs. The average inventory costs C_I for the two periods are here defined by

$$C_I = \frac{q}{2} * i * v\,.$$

The term $\frac{q}{2}$ represents the average inventory stock by assuming constant consumer's demand. The notation i corresponds to the inventory cost rate that typically depends on the value v of the underlying commodity. In our example, this rate is referred to our two periods and is assumed to be 0.01 for all agents.

Transportation costs C_T influence total logistics costs as follows:

$$C_T = \frac{Q}{q} * c_T(q)$$

Where Q is the quantity of the commodity flow, and the term $c_T(q)$ represents the cost per shipment requested from the Transport Service Provider Agent.

Consequently, total logistics costs are defined – in our example - as:

$$C = C_T + C_I$$

Shipper Agents choose frequency and transport service providers such that these costs are minimized. Or to put it in other words, when Shipper Agents are allowed to plan, they ask the set of Transport Service Provider Agents for transport tariffs for each possible shipment size (here $q = 10$ and $q = 5$), and select the configuration where total logistics costs are lowest. However, the Shipper Agent is only allowed to choose one TSP Agents for all its contracts.

Transport Service Provider Agent

We chose to model two TSP Agents. The first TSP Agent does not have any logistics facilities at its disposal, i.e. it can only offer direct transport services. The second TSP Agent operates a logistics network that consists of one transhipment centre. It is located where the interurban road (the spike) leaves the city. Additionally, both TSP Agents know all modelled Carrier Agents and can request services from all of them.

The *behaviour* of the TSP Agent consists of building transport chains, commissioning carriers and setting up a tariff table.

Transport chains are built according to a simple rule that is related to the available transhipment centres. If the TSP Agent has such a facility, all shipments are routed and transhipped via this transhipment centre, resulting in transport chains with two legs. If not, it offers direct transport services, i.e. transport chains with only one leg. For each leg, the TSP Agent selects an appropriate Carrier to operate the leg. In this experiment, this is done following a random model, which is further described below.

During the course of the simulation, the TSP Agent collects information about all available Carrier Agents and in the process creates its own tariff table. These tariffs are used to respond to Shipper requests. If the TSP Agent does not have any experience with the requested kind of shipment, it asks carriers for proposals. If it has, it quotes the price from its individual tariff table (however, as iterations go by, the TSP Agent still ask carriers regularly for proposals in order to consistently map transportation costs).

In our example, the tariffs are purely cost oriented. We assume that TSP Agents cannot influence the market price. Therefore, for a single leg transport chain from the industrial area to the location of a consumer, the transport tariff corresponds to the fee charged by the carrier who was selected to operate this leg. However, the tariff of a shipment which is transported via a transport chain with multiple legs is calculated as the sum of fees of the commissioned carriers, plus an extra transhipment cost of 2€ per transhipment and unit. When scoring its plan, the TSP Agents update their individual tariff table with the costs experienced in the last iteration.

Carrier Agent

There are four carriers in our experiment. Two of them are located in the middle of the northern edge of our checkerboard, whereas the other two are located in the middle of the southern edge. Each carrier is equipped with exactly one vehicle (see Table 2). We model three types of vehicles: heavy (40 units), medium (20 units) and light vehicles (10 units).

Table 2: Carrier Agents

Carrier	Location	Vehicle
Carrier 1	North	Light
Carrier 2	South	Light
Carrier 3	North	Medium
Carrier 4	South	Heavy

The behaviour of the carriers consists of vehicle routing and setting up a tariff table.

Vehicle routing is modelled with an optimisation approach based on the Ruin and Recreate principle (see Schrimpf et al. (2000)). The configuration of our VRP algorithm such as solution search strategies and its required parameters are chosen from the cited work. The algorithm is implemented in a way that it is possible to cope with a variety of vehicle routing problems (VRP). Here, we apply a setup in order to solve the VRP with pickup and deliveries.

The price setting strategy is cost oriented, as it is for TSP Agents. If the carrier already has some experience with similar shipments, it takes the price from its personal tariff table. If not, the associated cost is calculated based on its average marginal costs, i.e. the average marginal contribution to total tour costs. We approximate these costs by allocating the total tour costs (which we get by solving the VRP taking into account both existing shipments and the requested shipment) to each individual shipment such that the resulting shipment costs are proportional to its transport distance and capacity use.

When scoring its plan, the carrier updates its tariff table with the average marginal costs of each executed shipment.

It is important to mention again that both Shipper Agents and TSP Agents request and select offers from their business partners. If we designed offer selection such that always the offer with the lowest price would be selected, the simulation would quickly converge to a steady state, without giving agents any possibility to learn from the transport environment. For instance, a Carrier Agent operating a heavy vehicle might not experience its own consolidation advantages. The simulation result would always be significantly influenced by the first contract assignment. Therefore, we choose to design offer selection with a random model where the probability $prob(i)$ of choosing offer i depends on its price p_i as well as on all other requested prices in the following way:

$$prob(i) = \frac{\exp(-\beta * p_i)}{\sum_j \exp(-\beta * p_j)}$$

At β=0, offer selection is random on a uniform distribution over all offers. For increasing values of β, offer selection approaches 'best' offer selection. Therefore, in our selection model the value of β will increase in the course of the simulation (proportionally to the current iteration in relation to the total number of iterations). It starts with an initial value of 0.005 and ends with a value of 0.1.

Simulation

Table 3 lists the cost parameters for our simulation. For simplicity, we assume transport distance to be the main cost driver. Each model run consists of 50 iterations. Since, we applied random components, we conducted 10 model runs with different seed-values for the random number generator.

Table 3: Input data

Cost-Type	
cost per km	1 [€]
cost per transhipped unit	2 [€]
city toll per day	100 [€]
motorway toll per km	0.2 [€]

Simulation	
#Iteration	50
#Model runs	10

The basic steps of our simulation – that are described in the methodology chapter - can be summarised as follows:

Step 1: Initialising the world described above.

Step 2: All agents' plans are initially set up by cost calculations based on unused capacities. In other words, plans are generated based on the marginal costs of the first shipment.

Step 3: Mobility simulation.

Step 4: Scoring, i.e. cost calculations and allocations, and updating tariff tables.

Step 5: Re-planning. Exactly one Shipper Agent is randomly selected to re-plan. If the new plan exposes to be more advantageous than the old one (in terms total logistic costs), it is selected for execution in the next iteration. However, this probably changes the contracts of the involved agents and triggers TSP and Carrier Agents to re-plan their affected chains and routes. Independently of the latter, TSP Agents are allowed re-plan round about 20 percent of its transport chains, where they do not re-route shipments here rather than commission carriers. The latter changes affect the contracts of Carrier Agents who in turn respond by re-planning their vehicle routes.

Step 3 to Step 5 are repeated 50 times.

Cases

- **Case 1**: Reference.
- **Case 2**: Introduction of a new vehicle type. The 'heavy' carrier can now load 60 units.
- **Case 3**: Heavy vehicles in cities are prohibited.
- **Case 4**: Introduction of a city toll that amounts to 100€/day for medium vehicles, plus a toll for long distance transport amounting to 0.2 €/km.

Unless it is stated, all cases are built upon its preceding cases. For instance, when we introduce the toll, heavy vehicles are still prohibited, and the capacity of the heavy vehicle is still 60 units.

Results

The relaxed states of all model runs can be found in the annex. As mentioned above, for each case, we conducted 10 model runs where one run consists of 50 iterations. We average the results of these model runs yielding to the average distance travelled (see Table 4), the average volumes assigned to the transport service providers (see Table 5) as well as the average logistics costs of the shippers (see Table 6).

Table 4: Average transport distance (in meters)

Case	Carrier 1	Carrier 2	Carrier 3	Carrier 4	Total
Case 1	36,840	37,440	131,740	1,077,140	1,283,160
Case 2	18,420	0	94,300	752,580	865,300
Case 3	151,820	113,800	125,420	648,360	1,039,400
Case 4	194,820	235,660	34,800	664,580	1,129,860

Table 5: Average volumes assigned to Transport Service Providers

Case	TSP (with TSC)	TSP (without TSC)	Total
Case 1	0	160	160
Case 2	0	160	160
Case 3	160	0	160
Case 4	160	0	160

Table 6: Average logistics costs

Case	Shipper 1	Shipper 2	Shipper 3	Shipper 4	Total
Case 1	689	340	511	516	2,056
Case 2	556	229	351	381	1,518
Case 3	687	358	481	534	2,059
Case 4	741	393	511	573	2,217

In Case 1 – our reference scenario – all carriers travelled in total 1,283 kilometres. The highest share of total kilometres exhibits Carrier 4, which has a capacity of 30 units. Carrier 1 and 2, those with the small vehicles travel in average less than 40 kilometres. Both cannot compete with the carriers employing bigger vehicles (in terms of costs). When it comes to the contract assignment to TSP Agents, operating a single leg transport chain is the most favourable solution here. The total logistics costs of all shippers amount to 2,056 €, where shipper 1 - the one with the high value commodities - exhibits the highest amount of total logistics costs. Consequently, he decides to send the quantity of its commodity flows as two shipments in almost all model runs. In contrast, Shipper 2 sends the whole quantity at once, since transport costs of a second shipment would be higher than the savings in inventory cost (see shipper's frequencies in the annex).

In Case 2, we introduce a new vehicle with a capacity of 60 units, and we equip Carrier 4 with this vehicle. Carrier 4 can now use its large vehicle capacity to organize a round tour from the industry area to the customers, and thus has an enormous consolidation advantage. Total kilomtres travelled fall by up to 33 percent. Consequently, the TSP Agent offering only direct transport chains, can offer the lowest price, and is thus exclusively chosen by the Shipper Agents. Their total logistics costs can be reduced by 25 percent.

In Case 3, we implement a prohibition of heavy vehicles in cities. Here, it implies that Carrier 4 cannot operate in the urban city, thus the efficient round-tour in Case 2 is not feasible anymore. For simplicity, we still allow Carrier 4 to use urban roads to enter and exit the city area. The average solution found here is to operate a logistics network with the logistics centre at the entry point to the city. The TSP agent then gives the main leg (from the industry to logistics centre) to Carrier 4. Carrier 4 can then use its consolidation advantages in the long distance. Right from the logistics centre Carrier 1 to 3 take over the shipments. They then organize round tours from the logistics centre to final consumers. Total logistics costs rise as the result of the changes in the transport system, and amounts to 2,059 €.

In Case 4, we introduce a city toll for medium vehicles. The toll amounts to 100 € per day and vehicle and fall due for payment when entering the urban area. Additionally, we introduce a toll being charged for vehicles using the inter-urban road. This toll amounts to 0.2 € per kilometre. As can be seen, total vehicle kilometres increase by 10 percent and contracts are shifted from Carrier 3 to the carriers with the light vehicles. Total logistics costs increase by 10 percent either, which means transportation costs are the main driver here, and cannot be compensated by frequency decisions.

CONCLUSION

In this paper, we presented a multi-agent freight transport model in which logistics decisions are separated into different roles: shippers, which decide about shipment frequency, transport service providers, which create transport chains, and carriers, which plan tours and schedule vehicles. All agent types can consolidate on their respective level and realize economies of scale. The lowest tier of the model, which contains individual freight vehicles, was integrated into the MATSim traffic simulation to create an integrated model for freight and passenger traffic. Changes in passenger demand, disturbances in the traffic system or policy measures can be picked up by freight drivers and propagated upwards to influence decisions on the levels of vehicle scheduling and transport chain building, and further on the level of shippers.
The focus of the work has been on identifying and implementing the agent types and the information and decisions available to them, rather than on behavior, but the case study demonstrates that the computational framework can be used with behavior models of various complexities, from simple rule base logistics network planning to using sophisticated tour planning algorithms. We think that this multi-tiered framework can serve as a bridge between existing models that specialize on either transport chain building or vehicle routing.

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ANNEX

Table 7: Case 1 – Carrier vehicle meters

Run	Carrier 1	Carrier 2	Carrier 3	Carrier 4	Total
1	0	0	0	1125200	1125200
2	184200	0	184200	1125200	1493600
3	0	0	190200	1139200	1329400
4	184200	0	184200	945000	1313400
5	0	0	382400	1127200	1509600
6	0	190200	184200	951000	1325400
7	0	0	192200	1127200	1319400
8	0	0	0	1133200	1133200
9	0	0	0	1139200	1139200
10	0	184200	0	959000	1143200
Avg.	36840	37440	131740	1077140	1283160

Table 8: Case 1 – Transport volumes of TSP Agents

Run	TSP (with TSC)	TSP (without TSC)	Total
1	0	160	160
2	0	160	160
3	0	160	160
4	0	160	160
5	0	160	160
6	0	160	160
7	0	160	160
8	0	160	160
9	0	160	160
10	0	160	160
Avg.	0	160	160

Table 9: Case 1 – Total logistics costs of Shipper Agents

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4	Total
1	651	327	529	477	1983
2	653	308	482	468	1912
3	648	339	469	498	1954
4	759	352	520	546	2176
5	707	385	552	609	2254
6	695	324	544	478	2040
7	737	334	522	600	2193
8	679	336	435	483	1933
9	726	339	489	493	2046
10	641	354	570	507	2072
Avg.	689	340	511	516	2056

Table 10: Case 1 – Shipper's frequencies

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4
1	2	1.25	1.5	2
2	2	1.25	1.75	2
3	2	1.5	2	2
4	1.75	1	1.25	2
5	2	1.25	1.5	1.75
6	2	1.25	1.25	2
7	1.75	1	1.25	1.75

8	2	1.5	2	1.75
9	1.75	1	1.5	2
10	2	1	1.5	2
Avg.	1.925	1.2	1.55	1.925

Table 11: Case 2 – Carrier vehicle meters

Run	Carrier 1	Carrier 2	Carrier 3	Carrier 4	Total
1	0	0	0	762800	762800
2	0	0	188200	766800	955000
3	0	0	184200	768800	953000
4	0	0	378400	772800	1151200
5	184200	0	192200	586600	963000
6	0	0	0	772800	772800
7	0	0	0	772800	772800
8	0	0	0	776800	776800
9	0	0	0	774800	774800
10	0	0	0	770800	770800
Avg.	18420	0	94300	752580	865300

Table 12: Case 2 – Transport volumes of TSP Agents

Run	TSP (with TSC)	TSP (without TSC)	Total
1	0	160	160
2	0	160	160
3	0	160	160
4	0	160	160
5	0	160	160
6	0	160	160
7	0	160	160
8	0	160	160
9	0	160	160
10	0	160	160
Avg.	0	160	160

Table 13: Case 2 – Total logistics costs of Shipper Agents

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4	Total
1	542	209	336	347	1435
2	547	233	371	370	1521
3	550	219	343	398	1511
4	606	251	392	414	1663
5	529	242	309	384	1464
6	626	240	384	357	1606
7	546	234	345	390	1516
8	533	222	358	394	1508
9	548	202	339	383	1472
10	535	237	338	375	1486
Avg.	556	229	351	381	1518

Table 14: Case 2 – Shipper's frequencies

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4
1	2	1.75	2	2
2	2	1.25	1.75	2
3	2	1.75	2	2

4	1.75	1.25	1.75	2
5	2	1.25	1.75	2
6	1.75	1	1.5	2
7	2	1.25	1.75	2
8	2	1.75	1.75	2
9	2	1.25	2	2
10	2	1.5	2	2
Avg.	1.95	1.4	1.825	2

Table 15: Case 3 – Carrier vehicle meters

Run	Carrier 1	Carrier 2	Carrier 3	Carrier 4	Total
1	136000	122000	116000	680800	1054800
2	128000	146000	98000	680800	1052800
3	324200	142000	222200	680800	1369200
4	186000	110000	84000	680800	1060800
5	98000	142000	114000	680800	1034800
6	58000	92000	170000	518600	838600
7	158000	170000	60000	680800	1068800
8	122000	100000	122000	680800	1024800
9	162000	90000	112000	518600	882600
10	146000	24000	156000	680800	1006800
Avg.	151820	113800	125420	648360	1039400

Table 16: Case 3 - Transport volumes of TSP Agents

Run	TSP (with TSC)	TSP (without TSC)	Total
1	160	0	160
2	160	0	160
3	160	0	160
4	160	0	160
5	160	0	160
6	160	0	160
7	160	0	160
8	160	0	160
9	160	0	160
10	160	0	160
Avg.	160	0	160

Table 17: Case 3 – Total logistics costs of Shipper Agents

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4	Total
1	701	370	457	537	2066
2	663	348	456	510	1977
3	694	369	497	546	2107
4	705	368	516	540	2129
5	677	334	440	536	1988
6	658	340	472	490	1960
7	721	383	539	583	2226
8	677	359	485	517	2037
9	681	355	470	557	2063
10	690	354	475	522	2041
Avg.	687	358	481	534	2059

Table 18: Case 3 – Shipper's frequencies

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4
1	2	1.75	2	2
2	2	1	1.75	2
3	2	1.25	2	2
4	2	1.25	1.5	2
5	2	1.25	1.75	2
6	2	1	2	2
7	2	1	1.75	1.75
8	2	1.25	1.75	2
9	2	1	2	2
10	2	1.25	1.75	1.75
Avg.	2	1.2	1.825	1.95

Table 19: Case 4 - Carrier vehicle meters

Run	Carrier 1	Carrier 2	Carrier 3	Carrier 4	Total
1	210000	174000	30000	680800	1094800
2	208000	312200	28000	680800	1229000
3	234000	126000	24000	680800	1064800
4	96000	228000	64000	680800	1068800
5	124000	580400	30000	680800	1415200
6	370200	158000	30000	680800	1239000
7	220000	152000	30000	680800	1082800
8	204000	164000	24000	518600	910600
9	118000	228000	60000	680800	1086800
10	164000	234000	28000	680800	1106800
Avg.	194820	235660	34800	664580	1129860

Table 20: Case 4 - Transport volumes of TSP Agents

Run	TSP (with TSC)	TSP (without TSC)	Total
1	160	0	160
2	160	0	160
3	160	0	160
4	160	0	160
5	160	0	160
6	160	0	160
7	160	0	160
8	160	0	160
9	160	0	160
10	160	0	160
Avg.	160	0	160

Table 21: Case 4 - Total logistics costs of Shipper Agents

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4	Total
1	732	401	503	546	2182
2	734	399	525	609	2267
3	733	389	524	588	2233
4	883	407	519	591	2401
5	703	416	509	575	2203

6	736	385	508	591	2219
7	732	380	507	574	2194
8	684	383	510	547	2123
9	750	372	503	555	2180
10	723	394	501	553	2170
Avg.	741	393	511	573	2217

Table 22: Case 4 - Shipper's frequencies

Run	Shipper 1	Shipper 2	Shipper 3	Shipper 4
1	2	1.25	2	2
2	2	1	1.5	1.75
3	2	1.25	1.75	2
4	1.5	1.25	1.75	2
5	2	1.5	2	1.75
6	2	1.5	1.75	2
7	2	1.25	2	2
8	2	1	2	2
9	2	1.25	2	2
10	2	1.75	2	2
Avg.	1.95	1.3	1.875	1.95